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Study on the Performance of Brushless Doubly Fed Reluctance Generator under Voltage Harmonics

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ABSTRACT

This paper studies on the performance of brushless doubly fed reluctance generator (BDFRG) under the presence of voltage harmonics. The BDFRG is mainly used in wind electrical energy conversion system. The machine has two windings at stator- namely, power (primary) and control (secondary) windings. In this application, the power winding is directly connected to the weak electrical network, whose voltage may contain harmonics. The control winding is also connected to the same electrical supply via back-to-back (bidirectional/ dual) converter which also injects harmonics in this winding. Therefore, the performance of the machine under voltage harmonics condition needs to be studied. The MATLAB-SIMULINK software based simulation studies have been performed to show the performance of BDFRG under voltage harmonics situation.

Keywords- Brushless doubly fed reluctance generator (BDFRG), voltage harmonics, primary or power winding, secondary or control winding.

Nomenclature

v_1, v_2	Primary and secondary winding voltage respectively
i_1, i_2	Primary and secondary winding current respectively
ω_1, ω_2	Radian frequency of primary and secondary winding variables respectively
ω_r	Rotational speed in rad/sec
p_1, p_2	No. of pole pairs of primary and secondary winding
p_r	No. of pole pairs of rotor
T_e, T_m	Electromagnetic and mechanical torque
L_1, L_2	Primary and secondary winding total inductance respectively
L_{12}	Mutual inductance
R_1, R_2	Primary and secondary winding total inductance respectively
λ_1, λ_2	Primary and secondary winding flux linkage respectively

J	Moment of inertia of rotor
$*$	Conjugate operator
$\rightarrow$	Space vector notation
BDFRG	Brushless Doubly Fed Reluctance Generator

I. INTRODUCTION

In recent years, brushless doubly fed reluctance generator (BDFRG) is widely used in wind electrical energy conversion system [1]. The main advantages of BDFRG over its alternatives such as doubly fed induction generator etc are low cost, low maintenance, efficient [2], comfortable controllability, high reliability and better low-voltage ride-through capability. Construction wise, this machine has two three-phase windings of different pole numbers in stator - power or primary windings directly connected to the electrical supply and control or secondary windings connected to the same supply via dual converter [3]. A reluctance rotor has pole number different from both primary and secondary windings [4]. The two stator windings are magnetically coupled via the rotor. In wind electrical energy conversion system, the BDFRG can be operated under both sub- and super-synchronous speeds for extracting maximum power under variable wind speed conditions. This is conventionally known as maximum power point tracking (MPPT) control scheme. Various other control schemes such as scalar control [5], vector control [6, 7], direct torque control [8], direct power control [9], torque and reactive power control [10, 11] have been investigated in different published papers. The dual converter plays important role in the control strategy mentioned above.

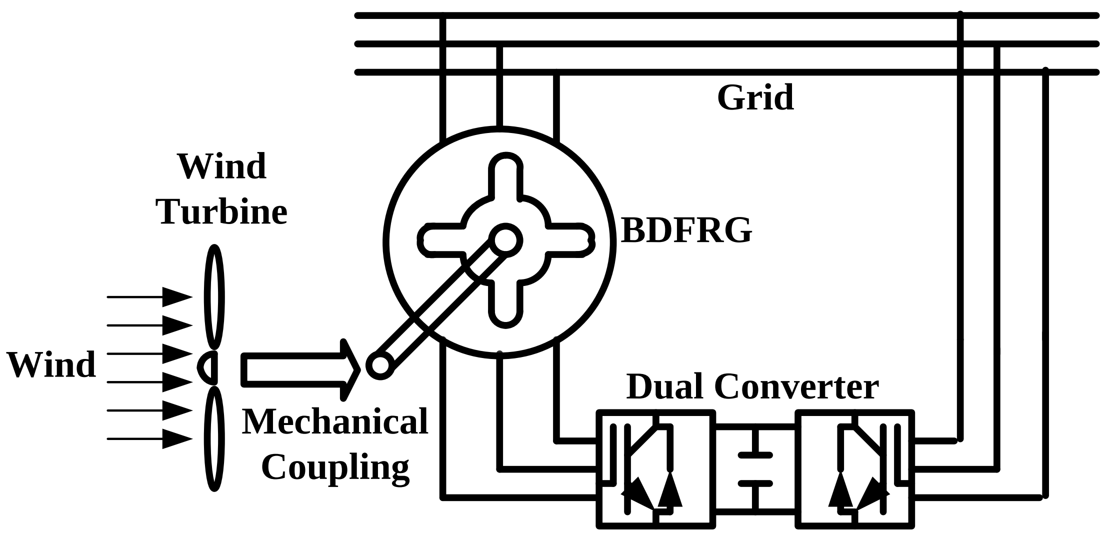


Fig. 1: Local grid connected BDFRG

The dual converter injects harmonics in the secondary windings. On the other hand, BDFRG based wind energy conversion system is normally connected to the local grid whose voltage may contain harmonics. However, the study on performance of BDFRG under voltage harmonic condition has not been yet noticed in the published works to the best of authors' knowledge. Therefore, this paper studies on the performance of BDFRG under voltage harmonic condition. The mathematical model of local supply connected BDFRG has been implemented using MATLAB-SIMULINK software. It has been observed that the voltage harmonics create pulsations in torque and speed. It can be mentioned here that the torque pulsations is detrimental to health of wind turbine and its mechanical components such as gear etc. In the study, the lower order predominant harmonics such as 5^{th} and 7^{th} order have been considered. This study will be helpful to design a strategy to nullify/reduce the undesired performance of BDFRG under voltage harmonics conditions.

The fundamentals and mathematical modeling of BDFRG are discussed in section 2. Section 3 presents the mathematical expressions of the performance variables of BDFRG under voltage harmonics condition. Section 4 shows the various results of simulation study. Section 5 presents the conclusions. The appendix and references follow the conclusion.

II. MATHEMATICAL MODELING OF BDFRG

The analysis and derivation of the various guiding expressions for modeling BDFRG has been elaborately presented in the reference [12]. The dynamic equations governing the behavior of BDFRG are expressed using space vector notation as:

$$\vec{v}_1 = R_1\vec{i}_1 + \frac{d\vec{\lambda}_1}{dt} + j\omega_1\vec{\lambda}_1$$

(1)

$$\vec{v}_2 = R_2\vec{i}_2 + \frac{d\vec{\lambda}_2}{dt} + j\omega_2\vec{\lambda}_2$$

(2)

$$\vec{\lambda}_1 = L_1\vec{i}_1 + L_{12}\vec{i}_2^{\,*}$$

(3)

$$\vec{\lambda}_2 = L_2\vec{i}_2 + L_{12}\vec{i}_1^{\,*}$$

(4)

Subscript 1, 2 corresponds to primary and secondary winding variable respectively.

The rotational speed of the rotor is decided by the angular frequency of primary and secondary variables as:

$$\omega_r = \omega_1 + \omega_2$$

(5)

The dynamic equation of the rotor can be given as,

$$T_m - T_e = J\frac{d\omega_r}{dt}$$

(6)

In Eq. (6), the electromagnetic torque can be mathematically related to the primary and secondary winding currents as:

$$T_e = j\frac{3}{4}p_r L_{12}[\vec{i}_1^{\,*}\vec{i}_2^{\,*} - \vec{i}_1\vec{i}_2]$$

(7)

The descriptions of symbols used in Eq. (1)-(7) are already included in the nomenclature section.

The governing d-q axis equations for primary and secondary side variables can be mathematically represented as:

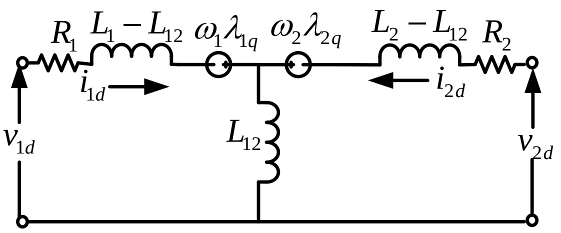
$$\begin{cases} v_{1d} = R_1 i_{1d} + \dfrac{d\lambda_{1d}}{dt} - \omega_1 \lambda_{1q} \\ v_{1q} = R_1 i_{1q} + \dfrac{d\lambda_{1q}}{dt} + \omega_1 \lambda_{1d} \end{cases}$$

(8)

$$\begin{cases} v_{2d} = R_2 i_{2d} + \dfrac{d\lambda_{2d}}{dt} - \omega_2 \lambda_{2q} \\ v_{2q} = R_2 i_{2q} + \dfrac{d\lambda_{2q}}{dt} + \omega_2 \lambda_{2d} \end{cases}$$

(9)

The d-q axis equivalent circuit diagram of BDFRG is shown in Fig. 2.



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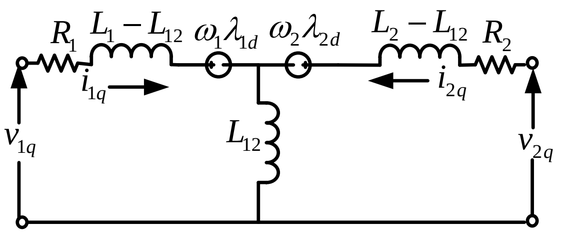


(b)

Fig. 2: (a) d-axis model, (b) q- axis model of BDFRG

III.PERFORMANCE UNDER VOLTAGE HARMONICS

The three-phase voltage expressions for primary and secondary windings are given in Eq. (10):

$$v_{1,2a}=\left\{V_{fm}\sin\left(\omega_{1,2}t+\phi_1\right)+V_{3m}\sin\left(3\omega_{1,2}t+\phi_3\right)+V_{5m}\sin\left(5\omega_{1,2}t+\phi_5\right)+V_{7m}\sin\left(7\omega_{1,2}t+\phi_7\right)\right.$$

$$v_{1,2b}=\begin{cases}V_{fm}\sin\left(\omega_{1,2}t+\phi_1-\frac{2\pi}{3}\right)+V_{3m}\sin\left[3\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\phi_3\right]+V_{5m}\sin\left[5\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\phi_5\right]\\+V_{7m}\sin\left[7\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\phi_7\right]\end{cases}$$

$$v_{1,2c}=\begin{cases}V_{fm}\sin\left(\omega_{1,2}t+\phi_1+\frac{2\pi}{3}\right)+V_{3m}\sin\left[3\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\phi_3\right]+V_{5m}\sin\left[5\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\phi_5\right]\\V_{7m}\sin\left[7\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\phi_7\right]\end{cases}$$

(10)

Eq. (10) includes the fundamental component and harmonics up to 7th order. Here, lower order predominant harmonics are considered as they mainly influence on the speed and torque pulsation of the machine. The voltage harmonic creates current harmonic in the respective winding. The interaction of primary and secondary current harmonics creates the electromagnetic torque pulsation in BDFRG as per Eq. (7). This torque pulsation produces oscillation in the rotor speed, which can be decided from Eq. (6).

The corresponding three-phase current expressions are given by:

$$i_{1,2a}=\left\{I_{fm}\sin\left(\omega_{1,2}t+\theta_1\right)+I_{3m}\sin\left(3\omega_{1,2}t+\theta_3\right)+I_{5m}\sin\left(5\omega_{1,2}t+\theta_5\right)+I_{7m}\sin\left(7\omega_{1,2}t+\theta_7\right)\right.$$

$$i_{1,2b}=\begin{cases}I_{fm}\sin\left(\omega_{1,2}t+\theta_1-\frac{2\pi}{3}\right)+I_{3m}\sin\left[3\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\theta_3\right]+I_{5m}\sin\left[5\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\theta_5\right]\\+I_{7m}\sin\left[7\left(\omega_{1,2}t-\frac{2\pi}{3}\right)+\theta_7\right]\end{cases}$$

$$i_{1,2c}=\begin{cases}I_{fm}\sin\left(\omega_{1,2}t+\theta_1+\frac{2\pi}{3}\right)+I_{3m}\sin\left[3\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\theta_3\right]+I_{5m}\sin\left[5\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\theta_5\right]\\I_{7m}\sin\left[7\left(\omega_{1,2}t+\frac{2\pi}{3}\right)+\theta_7\right]\end{cases}$$

(11)

In Eq. (10) and (11), 'ϕ'and 'θ' indicates phase angle of voltage and current respectively. Both Eq. (10) and (11) are applicable for primary and secondary windings as both windings are situated in the stator. Thus subscript 1 or 2 is used in the equations. The subscript 'f' denotes fundamental component.

The expression of electromagnetic torque can be rewritten under harmonic condition as:

$$T_e = \begin{cases} j\frac{3}{4}p_r L_{12}[\left(\vec{i}_{1f}+\vec{i}_{15}+\vec{i}_{17}\right)^*\left(\vec{i}_{2f}+\vec{i}_{25}+\vec{i}_{27}\right)^* \\ -\left(\vec{i}_{1f}+\vec{i}_{15}+\vec{i}_{17}\right)\left(\vec{i}_{2f}+\vec{i}_{25}+\vec{i}_{27}\right)] \end{cases}$$

(12)

In Eq. (12) the first and second number in the subscript indicates winding type and harmonics order respectively.

IV. RESULTS

The simulation study is performed using MATLAB-SIMULINK software. The mathematical modeling of BDFRG has been implemented in software platform using the dynamic equations mentioned in section 2. The specifications of BDFRG used in the study are given in Appendix. At first, the machine is operated under normal condition. Then, the machine is operated under voltage harmonics condition. The various responses are compared and presented in subsequent figures. The primary winding voltages under normal voltage and harmonic voltage conditions are shown in Fig. 3. The secondary winding voltages under both cases are presented in Fig. 4. The corresponding primary and secondary windings current responses under normal and harmonics conditions are given in Fig. 5 and 6 respectively. The mechanical input torque is shown in Fig. 7. The obtained electromagnetic torqueses for both cases are given in Fig. 8. The corresponding rotational speed waveforms are shown in Fig. 9.

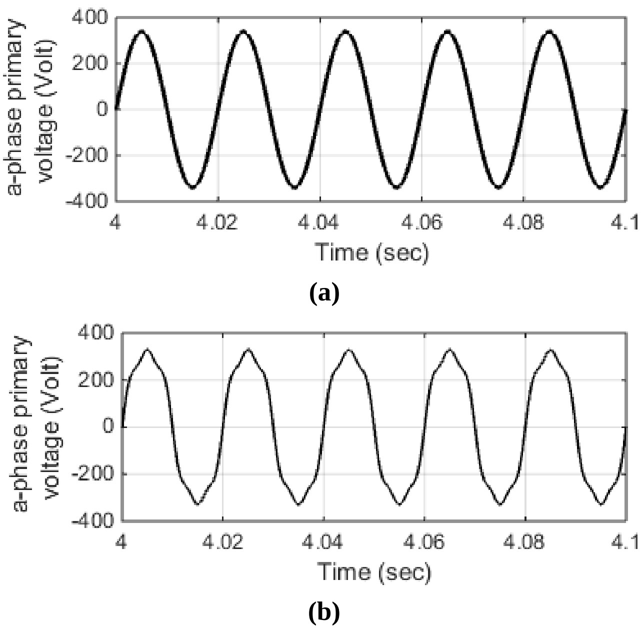
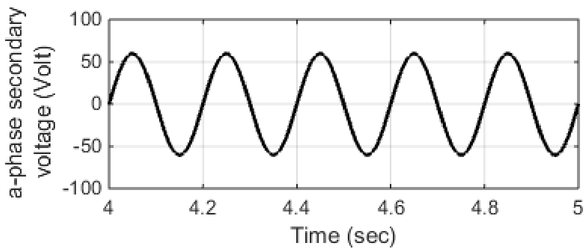


Fig.3: a-phase primary voltage under (a) normal and (b) harmonic condition



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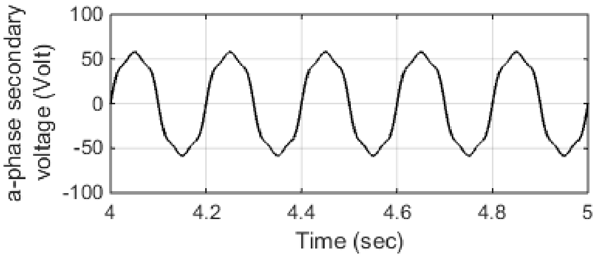
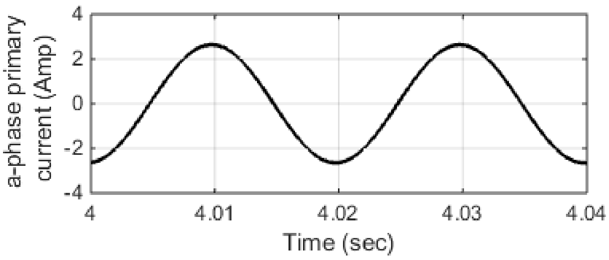


(b)

Fig.4: a-phase secondary voltage under (a) normal and (b) harmonic condition



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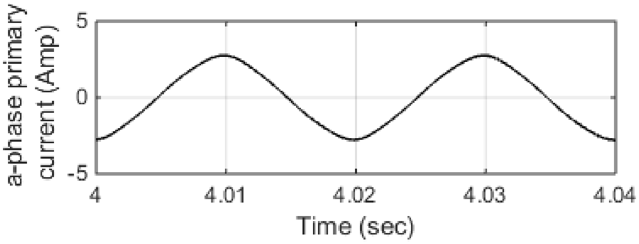
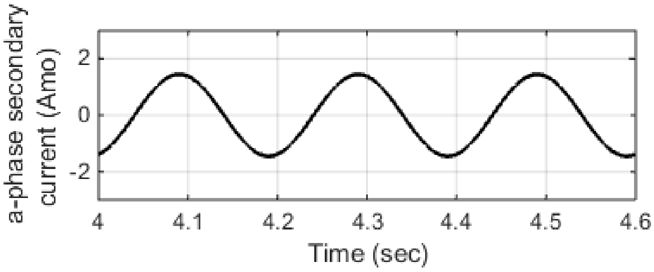


(b)

Fig.5: a-phase primary current under (a) normal and (b) harmonic condition



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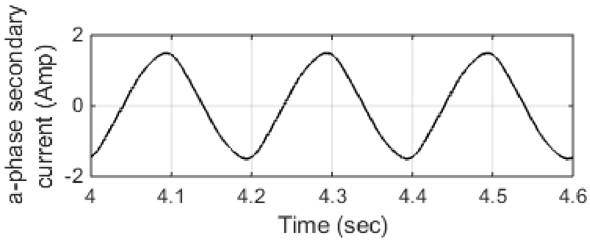

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Fig.6: a-phase secondary current under (a) normal and (b) harmonic condition

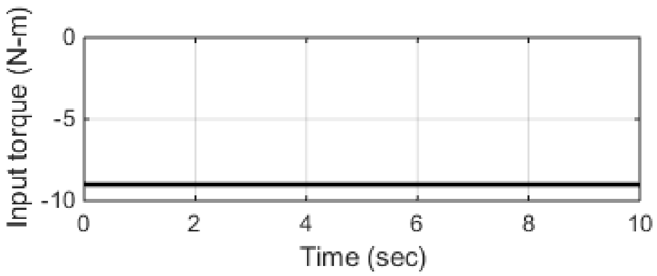
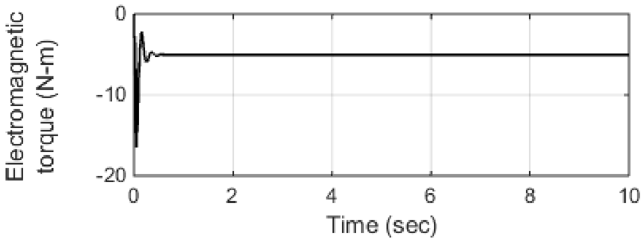
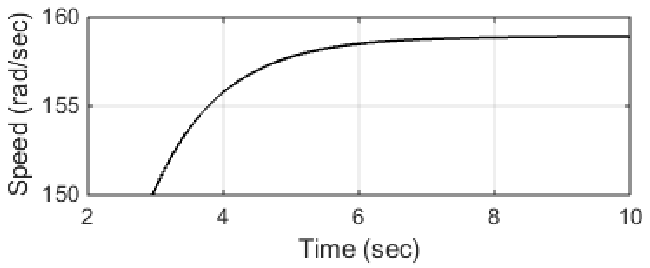


Fig.7: Plot of input mechanical torque



(a)



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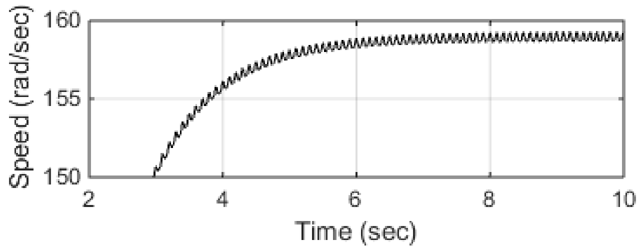

(b)

Fig.9: Rotational speed under (a) normal and (b) harmonic condition

TABLE 1
PARAMETERS OF BDFRG

PARAMETERS	VALUES
Power	1.5 kW
Voltage	415 V
R_1, L_1	10.7 Ω, 0.407 H
R_2, L_2	12.68 Ω, 1.256 H
L_{12}	0.57 H
J	0.1 kg/m^2
p_1, p_2, p_r	6,2,4

V. CONCLUSION

This paper focuses on the systematic study on the performance of BDFRG under voltage harmonics condition. The voltage harmonics up to 7th order have been considered for both primary and secondary windings. These harmonics create distortions in both primary and secondary windings currents. These distorted currents produce pulsations in both torque and speed. These undesired effects can be detrimental for the components of wind energy conversion system such as wind turbine, gears etc. The study has been performed using MATLAB-

SIMULINK software. In future, the strategy will be developed to minimize undesirable effects of local grid connected BDFRG under voltage harmonics conditions.

Appendix

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